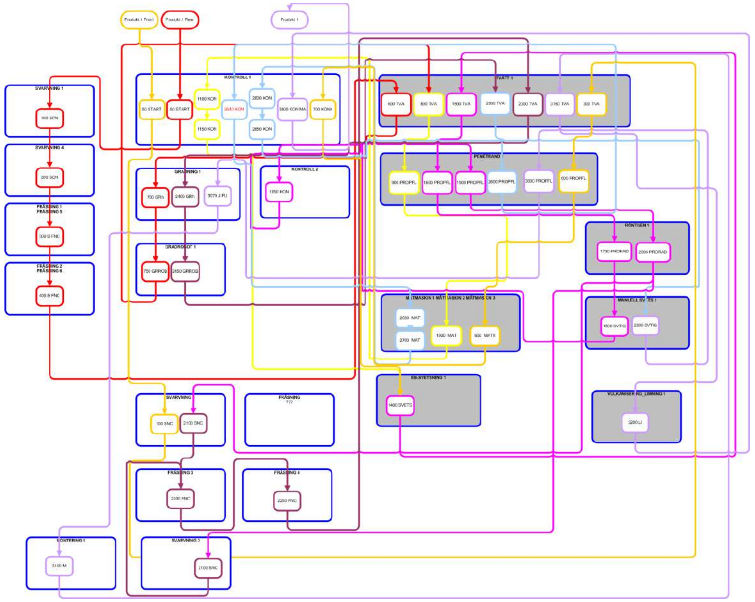

(The depicted system includes 39 resources, 242 type of jobs)
–Source: GKN

Mathematical optimization of the tactical allocation of machining resources for an efficient capacity utilization in aerospace component manufacturing

A talk on problem description and approach

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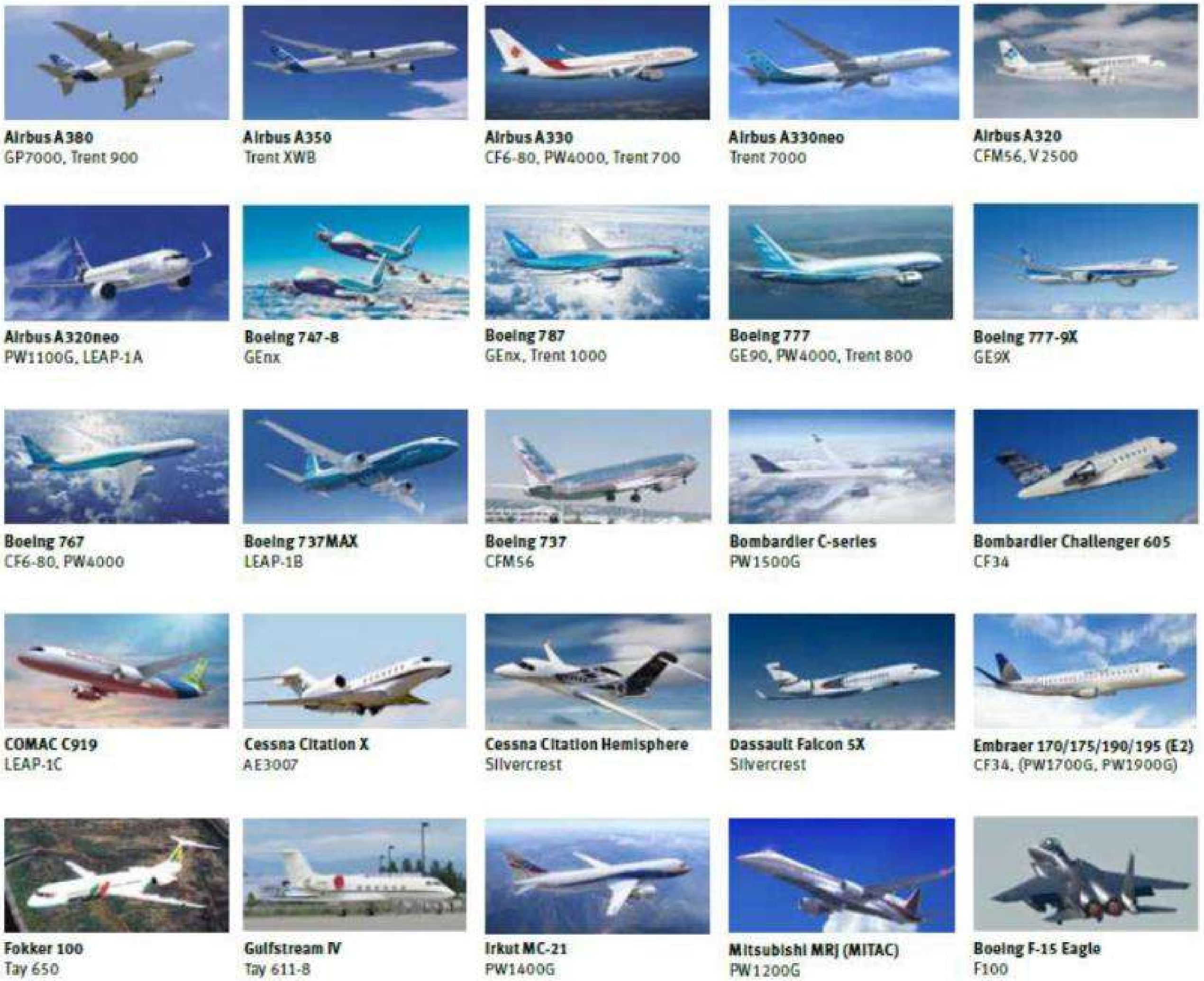
GKN Overview

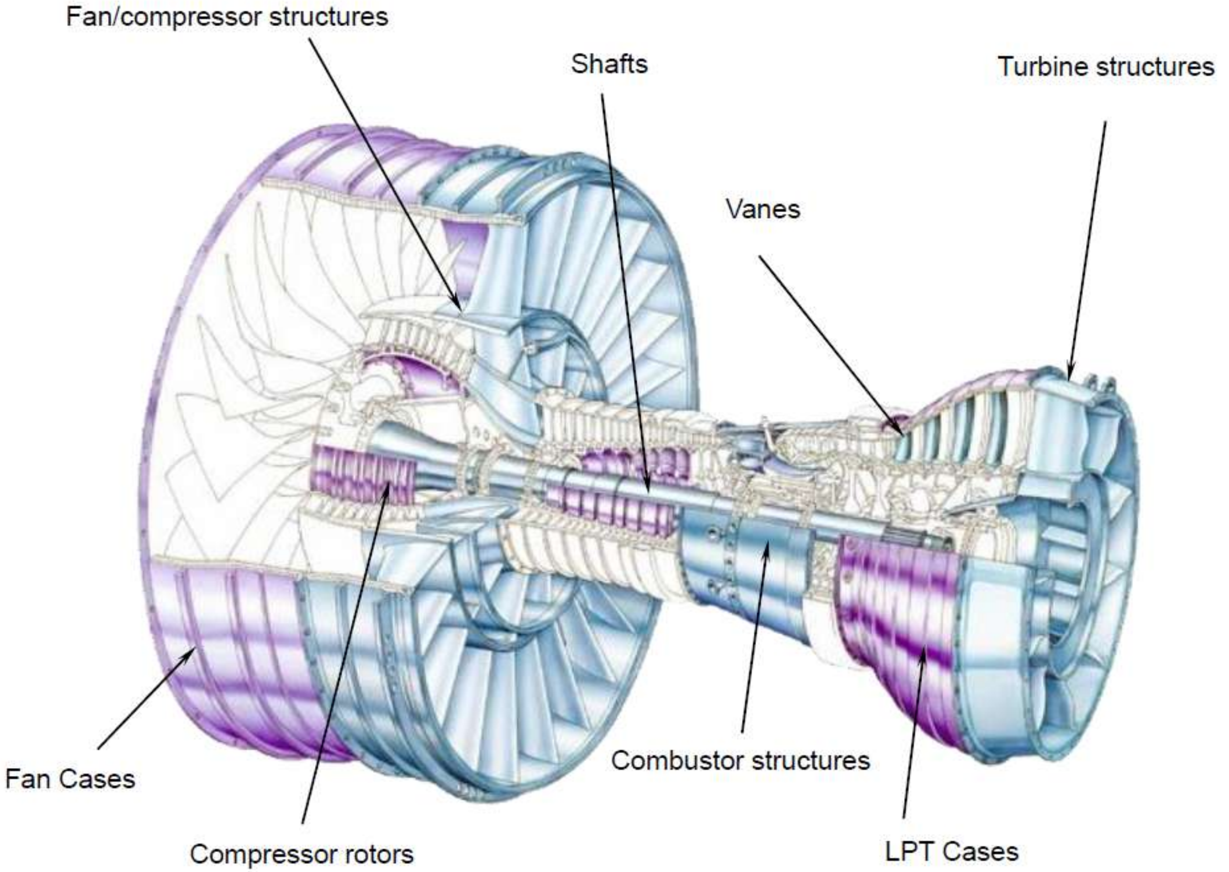
- Products
- Steps in manufacturing
- Logistics context
- New product introduction

GKN Aerospace Engine Systems



Source: GKN Aerospace

GKN Aerospace's component specialization



Source: GKN Aerospace

Manufacturing context

- Following are the main steps to manufacture a part or a product:
  - ❑cutting (milling, turning, drilling, and grinding)
  - ❑welding
  - ❑assembly
  - ❑heat/surface treatments
  - ❑control/measurement
- The factory is organized in **several functional oriented production** shops, and each production shop is organized as a **job-shop**
- All machines are bulky and fixed to the ground in **2—5 meter deep pits**. Thus, the factory can be adapted to changing product mix only to a very limited extent

Production logistics: Reducing tied-up capital, and efficient capacity utilization

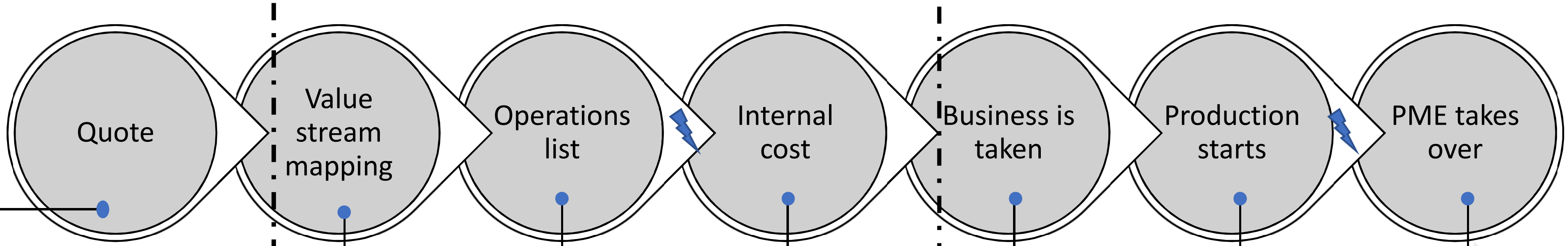
System environment

- ❑ Low volumes, and uncertain demand
- ❑ High precision requirements resulting in rework
- ❑ Complex, and time-consuming process planning while introducing new products
- ❑ Chosen allocations are expensive to change
- ❑ Heavy machines, that are, impossible to move
- ❑ Resources are shared by multiple products/parts
- ❑ Impossible to build, and maintain perfect production flows, partly due to process variability

Focus

- ✓ Increase the utilization of machines without increasing the tied-up capital or decreasing the delivery performance
- ✓ Improve the abilities for the most popular machines to better handle demand variations
- ✓ Balanced utilization of production resources to maximize overall shop capacity

New product introduction is tied-up with the allocation process



- Chief manufacturing engineer involved
- If the product is not well-know more experts are involved

- Decision regarding value stream
- Checking whether enough capacity is available

- Manufacturing experts prepare operations list
- Based on operations list, internal cost is assessed
- Internal cost accounting method influences resource allocation decisions

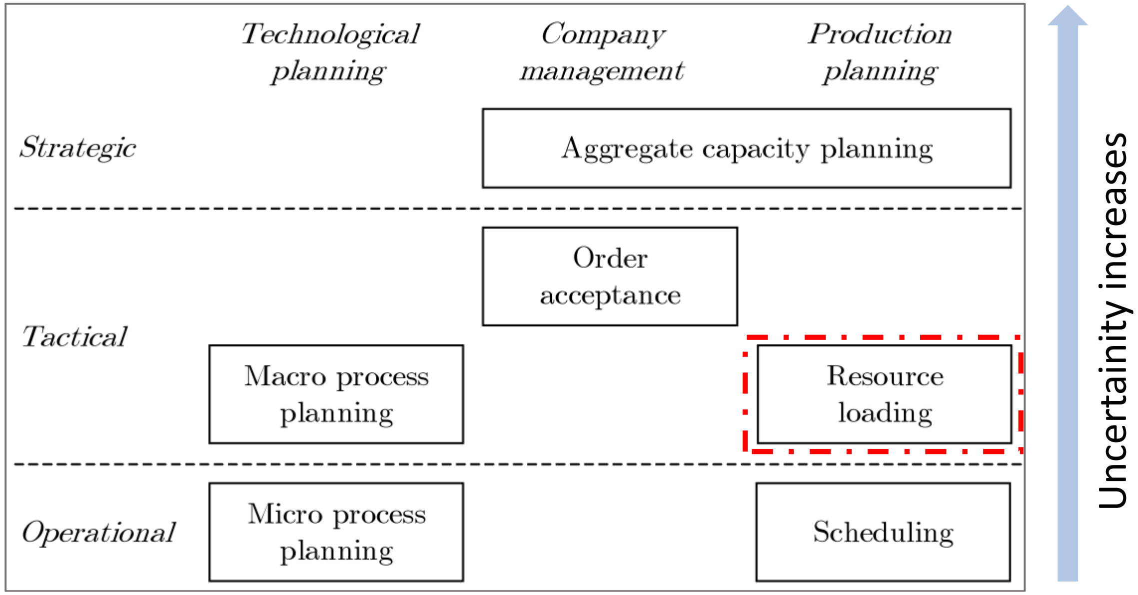
- New product introduction (NPI) leader is responsible for introducing new product
- After introduction, product manufacturing engineer (PME) is responsible
- Allocations are forcibly changed due to current demand/capacity scenarios which results in disturbances

Project background

- What is Tactical resource allocation?
- Difference between tactical resource allocation and scheduling
- Why is Tactical resource allocation necessary?

Tactical resource allocation (definition)

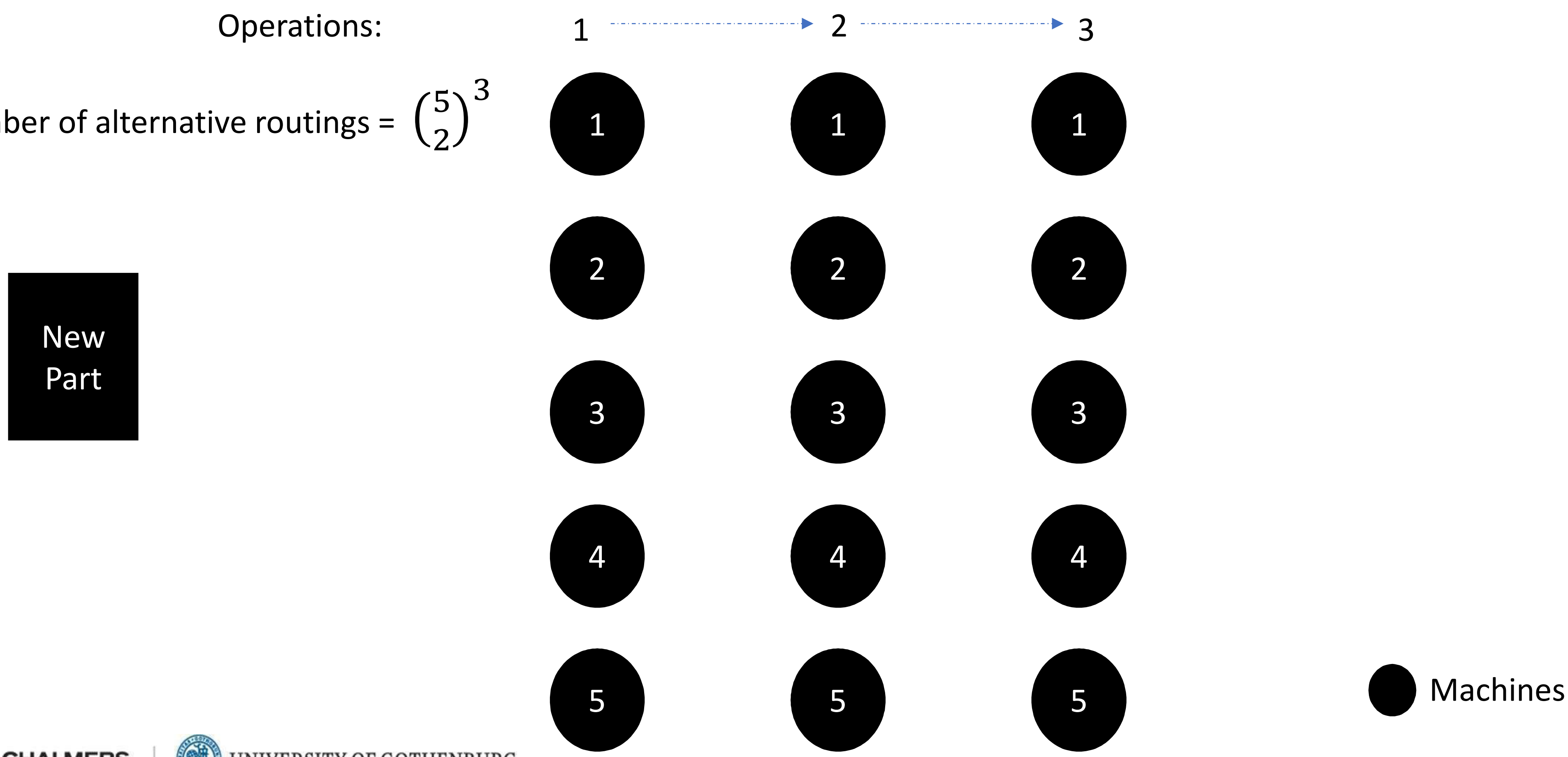
- Tactical resource planning or resource loading on the medium to long-range planning horizon **identify which production processes that need to be developed**
- The processes then developed **constitute the solution space** for the scheduling
- The tactical planning therefore **differs significantly from the short-term planning (scheduling)**
- Tactical resource allocation also requires **inputs from manufacturing experts on compatibility and suitability of assigning a product/part's operation to a machine**



Source: Giebels et al., 2000

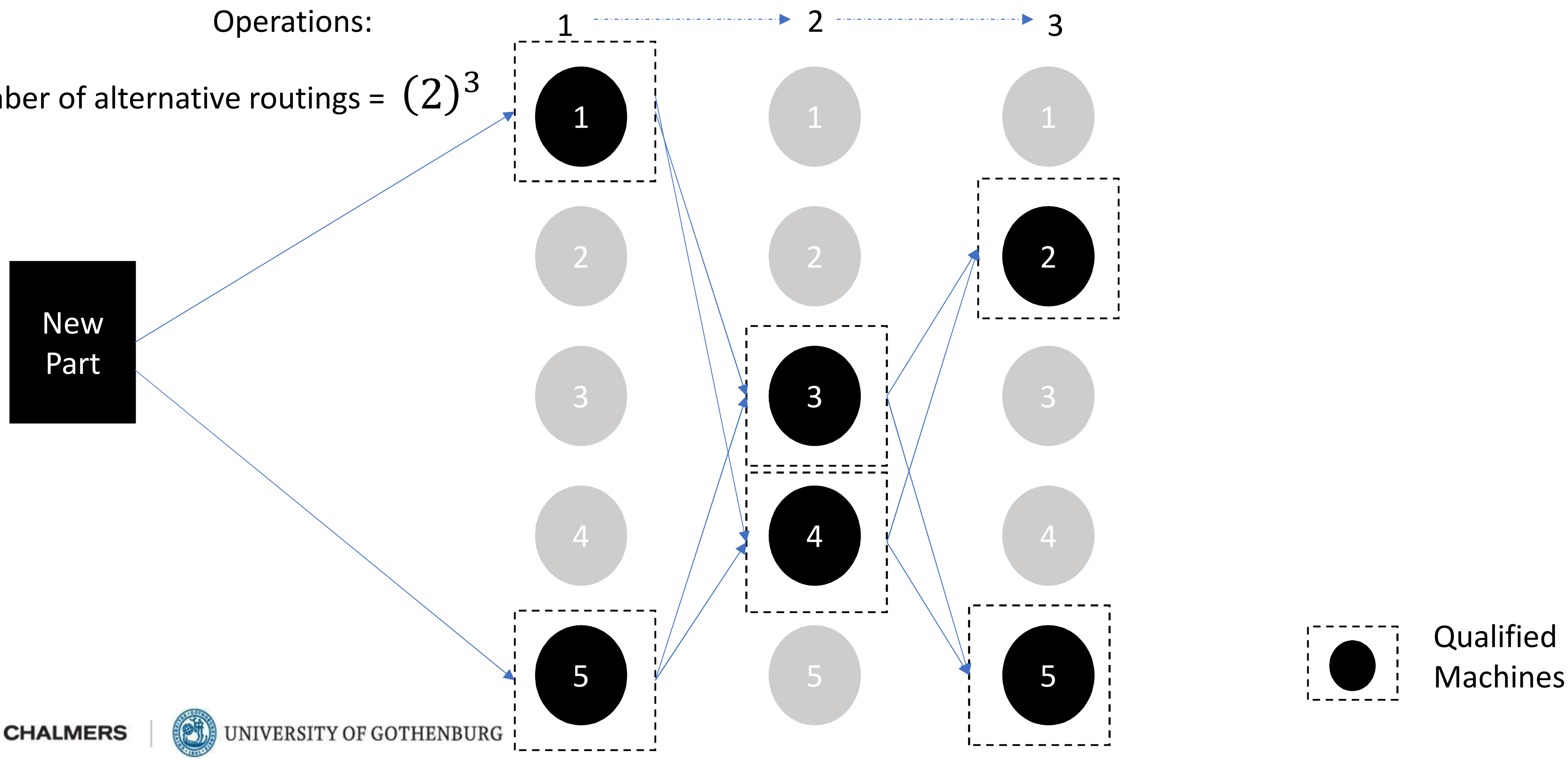
Example: Tactical resource allocation (TRA) for a new part or product

Number of alternative routings = $\binom{5}{2}^3$



Limitation on the number of alternative routings is a result of TRA

Number of alternative routings = $(2)^3$



Why is tactical resource allocation necessary?

- **To limit the number of qualification for new product**: Any new product requires machines to be qualified for its operations, which involves detailed technical assessment, simulations, validation, and testing

- **Customer approval**: Any qualification of a machine for an operation has to be approved by customers which may take several months. Thus, tactical allocations have to be done well in advance

- **Man-hours**: An allocation requires skilled personnel for CNC programming, and sometimes there is need to buy new fixtures, and tools in advance

- **Thus, tactical allocation decisions once made are difficult to change** and stay with the company for many years

Current status

- How is TRA done right now?
- Capacity balancing losses and its effects

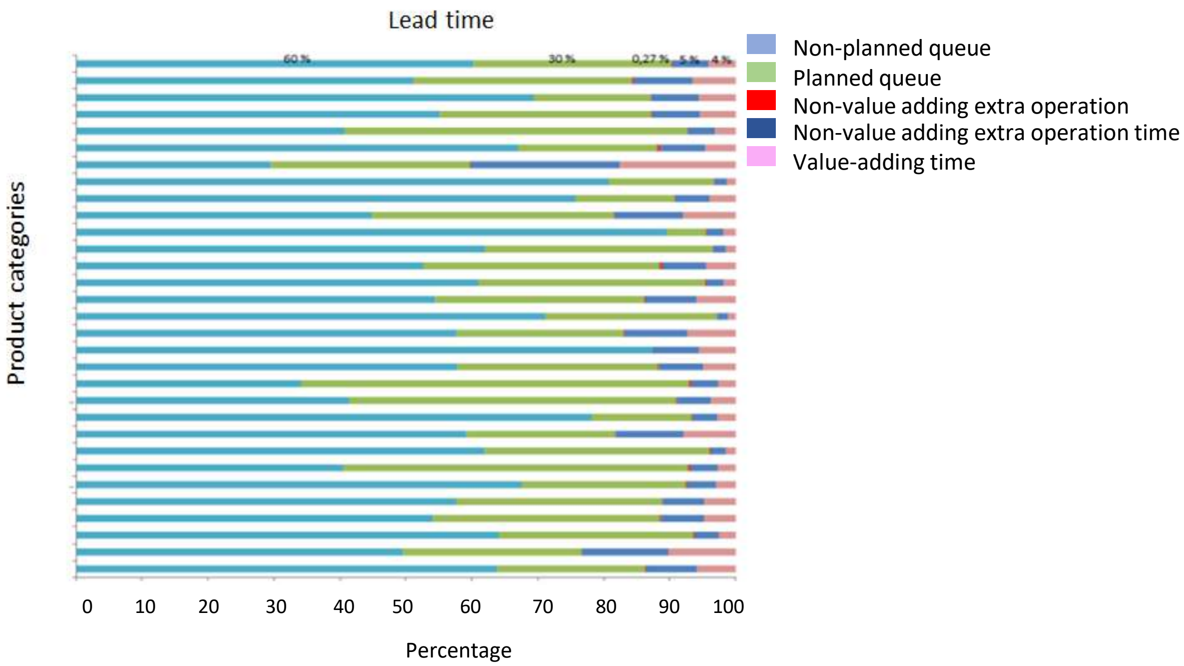
Tactical allocation is driven by short-term focus on the product cost

- Some machines are attractive as they are faster and/or more capable
- These machines are preferred as it **minimizes the total time** a product spends in machines
- Capacity planners' perspective is not represented well in tactical allocations
- Due to traditional accounting principles such approaches have been preferred as highlighted in (Myrelid and Olhager, 2019)
- Thus, such approaches have misleading impact on the internal product cost and thus, result in sub-optimal allocations from capacity planning perspective
- With the help of an appropriate objective function/s (a measure the 'goodness' of allocations) to find the best possible routings

Effect of minimizing machining hours: Capacity utilization imbalance

Too high loading on some resources results in queuing. This effect is exacerbated by varying demands and complex flows (due to shared resources). By avoiding unnecessary imbalances in resource utilization, excessive queuing can be avoided.

- **Excessive queuing have the following effects**:
  - Long queue times in front of machines
  - Long lead times
  - Delivery disturbances
  - Over-time usage
  - Inefficient utilization of available resources
  - Reduced overall capacity
  - Reduced income



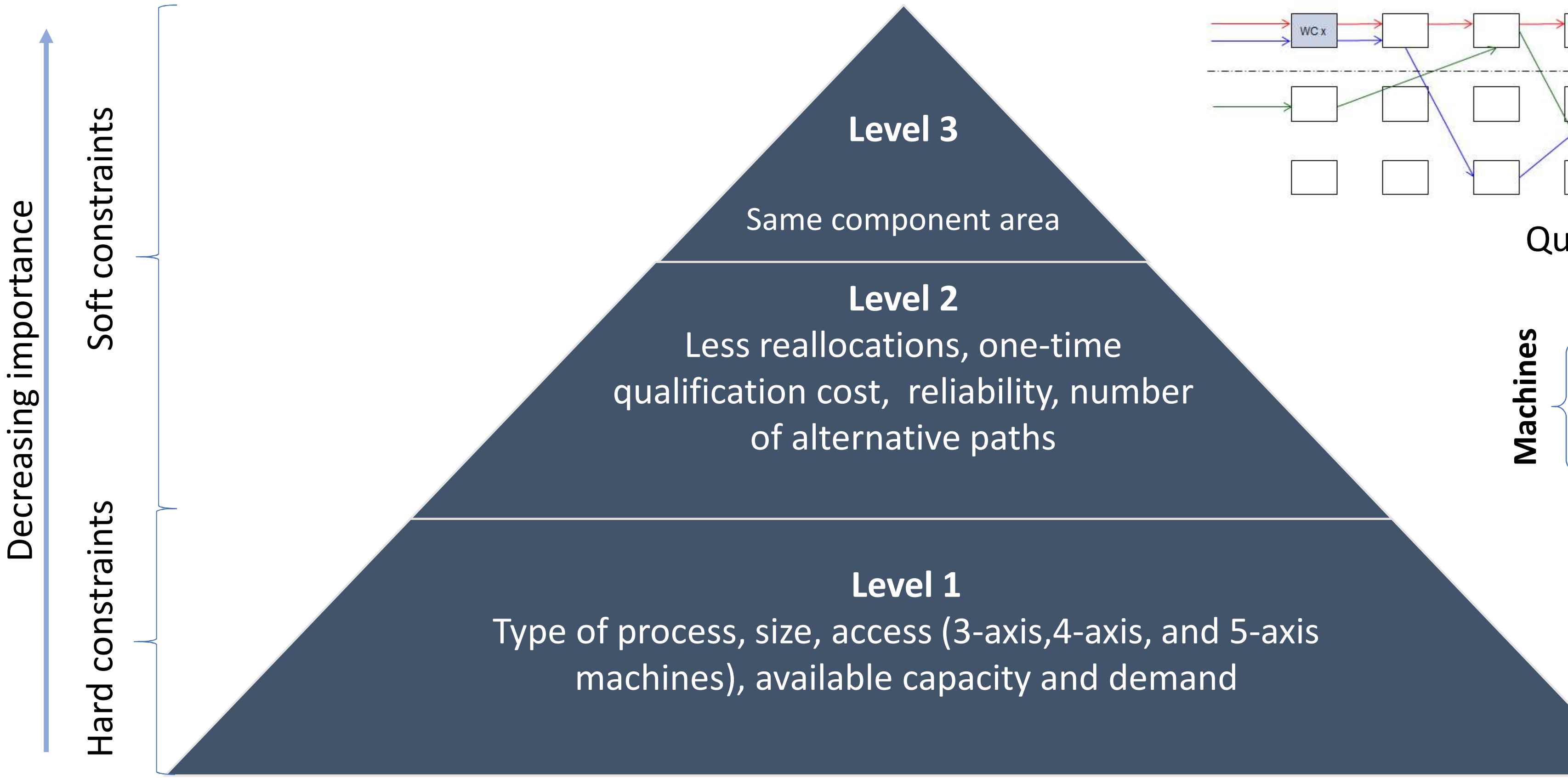
Scope and problem description

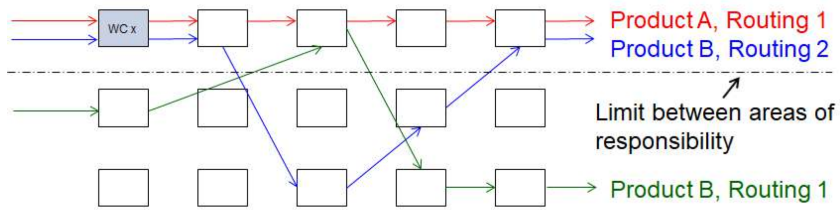
- Which type of machines are we considering?
- What are the limitations and degrees of freedom? – Constraints (*Hard and Soft*)

Tactical resource allocation - Scope

- **Planning horizon** – It can be **4–8 years divided into monthly or quarterly time-periods**
- **Products** – **Both existing and new**. However, the existing products already have established qualified machines, so we already know probable routings for the existing products. A new product requires qualifications
- **Machines** – All cutting machines such as milling, turning, drilling and grinding
- **Demand** – The demand has to be met in each time-period. These are forecasted figures based on current contractual commitments and projections
- **Inputs required** - Processing time, set-up time, demand , size, tolerance requirements, compatibility and operations list

Hard and soft constraints





Qualifications matrix

Jobs (columns) × Machines (rows)

0	1	0	0	0	1	1	1
0	1	0	1	0	1	1	1
0	1	0	1	0	1	1	1
0	1	0	1	0	1	1	1

Compatibility matrix

Jobs (columns) × Machines (rows)

0	1	0	1	0	1	1	1
0	1	0	1	0	1	1	1
0	1	0	1	0	1	1	1
0	1	0	1	0	1	1	1

Mathematical optimization

- Why optimization?
- How do we measure ‘goodness’ of feasible allocations?

Mathematical optimization ‘To get provable best possible solution’

- Mathematical optimization is the selection of a best solution from a set of available alternatives

- The solutions obtained through mathematical optimization provide a bound (guarantee) on the solution quality

  Optimality gap = $\frac{Best \text{ objective value } found - Best \text{ objective value } possible}{Best \text{ objective value } possible}$. Hence, in some cases when it takes long time to achieve optimality, we stop at $x\%$ optimality gap

- Alternatives to mathematical optimization are rules, heuristics, and meta-heuristics, but they do not provide such bounds on the quality of solution

- An optimization model consists of two parts:

  - the **objective** as function of the decision variables

  - the **constraints** that restricts the decision variables

Objective function – capacity balancing

- Some notations before we mention the objective functions:
  - x_{ijk}^{t} : represents the number of orders of job type (i, j) in machine k at time-period t
  - C_k : Capacity (hours) available in machine k at each time-period
  - ζ: Threshold utilization ($0 \leq \zeta \leq 1$)
  - p_{ijk}: Processing time for job type (i, j) in machine k (includes average set-up time)
  - Let X be the set of feasible routings satisfying Level 1 constraints
  - All the routings $x \in X$ satisfy level 1 constraints
  - There are two alternative objective functions which can be defined as to:
    - $Minimize \sum_t \sum_k max\left\{\frac{1}{C_k} \sum_i \sum_j p_{ijk} \ x_{ijk}^{t} \ - \zeta, 0\right\}$
    - $Minimize \sum_t \max_k \left\{\max\left\{\frac{1}{C_k} \sum_i \sum_j p_{ijk} x_{ijk}^{t} \ - \zeta, 0\right\}\right\}$

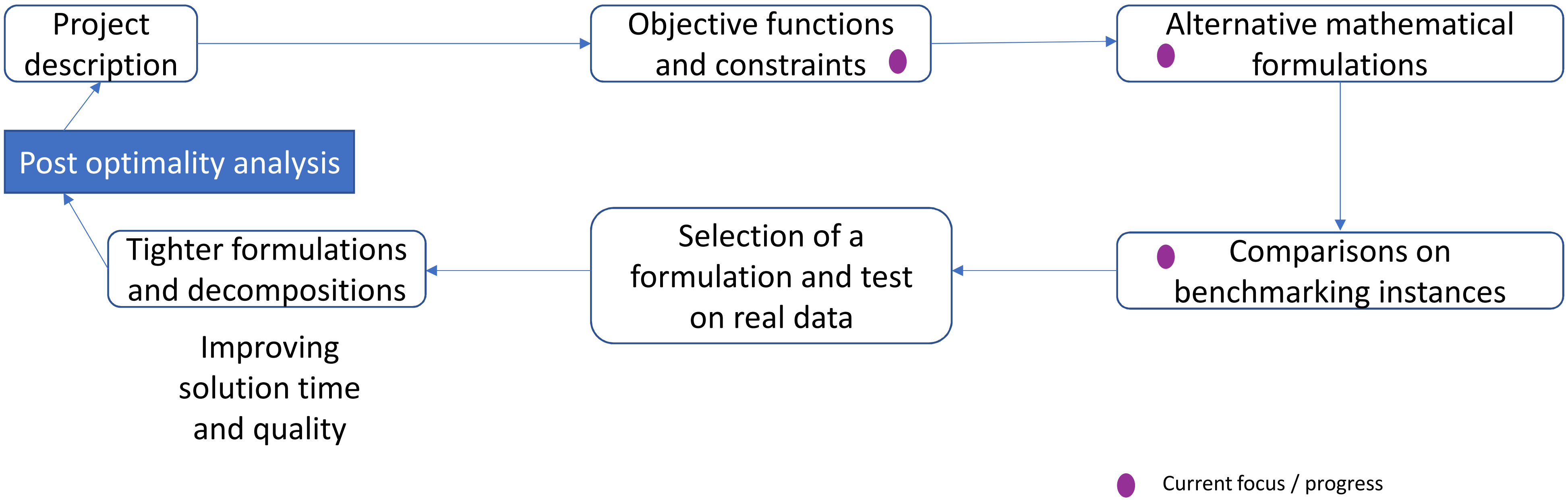
Industrial scale problem is difficult to solve to optimality

- ~***100–150*** **cutting operations related machines**
- Scope of ***~4—8* years**
- ***~4500* unique job type** (part+operations)
- If we assume a multi-period problem of ***5* years.** So, the number of time-periods (quarters) is ***20***
- Number of variables (arcs): *<= n*m*, where ***n*** **is the number of jobs** and ***m*** **is the number of machines**
- $\mathrm{m} = 100 * 20 = 2\,000$
- $\mathrm{n} = 4500 * 20$ = 90 000
- An upper bound on the number of variables (arcs) in the model is **180.000.000 and 9.500.000 constraints. This impacts the time it takes to solve the problem to optimality**

Expected results

- A decision making tool, which **enables faster, and better adaptation of the production system** to changing conditions
- The tool can be used not only when **introducing of new products, but also when there is change in demand and phasing out of old products or machines**
- Leverage knowledge of **manufacturing experts, and codify it in the form of a model**
- If we assume that there are approximately 500.000 machine hours available annually (cutting), then
  - ✓ If we succeed to use 2% more hours, that results in a capacity increase of 10.000 hours
  - ✓ 10.000 hours that can be used for new products in the shop, products that will increase revenue
- Improved **delivery performance**
- We also expect to **bring down lead time of products, which will release tied-up capital**

Overview


Project description
Objective functions and constraints
Alternative mathematical formulations
Post optimality analysis
Tighter formulations and decompositions
Selection of a formulation and test on real data
Comparisons on benchmarking instances
Improving solution time and quality
Current focus / progress

Thank you!

Questions?